Paste 2010 — R.J. Jewell and A.B. Fourie (eds)
© 2010 Australian Centre for Geomechanics, Perth, ISBN 978-0-9806154-0-1
doi:10.36487/ACG_rep/1063_24_Dunmola

Solute mass transport and atmospheric drying of high-density gold tailings

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Abstract

The accumulation of salts on the surface of thickened tailings is well-known to suppress evaporation and consolidation, thereby having both negative economic and environmental implications for surface deposition operations. The current research studied and related the 1D mass transport of dissolved solute within a layer of acid-generating thickened gold tailings to salt crust formation and evaporation using a model wax column technique. The electrical conductivity, matric suction, total suction and gravimetric water content at 1 cm intervals of a column of desiccating thickened tailings was determined over a period of 15 days and related to measured evaporation rates over the same period. Results from this paper showed evidence of salt accumulation at the top 1 cm of thickened tailings layer, which reduced the rate of evaporation after 12 days. Osmotic suction was observed to be the major mechanism of reduction in evaporation rate by salts, as opposed to any physical crust effects. Therefore, it may be possible to anticipate suppression of evaporation by salts through modelling ion transport, a technique that could be used to optimise thickened tailings deposition schemes with respect to controlling salt accumulation.

1 Introduction

The surface deposition of thickened tailings is gradually becoming widely acceptable as a safer alternative to the conventional storage of tailings slurry behind retention dams (Newman, 2003) due to the risk of catastrophic failure associated with the latter (ICOLD, 1989). Surface deposition of thickened tailings offers a number of additional benefits: reduced footprints for disposal, reduced contaminated seepage, improved stack stability, increased water recycling and improved ease of closure. Surface deposited thickened tailings undergo densification through a combination of mechanisms, namely; hindered settling, desiccation and self-weight consolidation (Simms et al., 2009). Desiccation is a major contributor to tailings densification and consequently improves the shear strength and bearing capacity of deposited stacks (Rasaam and Williams, 1999; Fujiyasu and Fahey, 2000).

Pore-water salinity is known to impede evaporation and consequently slows down the rate of shear strength gain in tailings stacks. The formation of salt crust at the surface has been implicated in the reduction of evaporation rates from soil and tailings to just about 10% of the potential rate (Chen, 1992; Newson and Fahey, 1997). The three mechanisms by which salinity lowers evaporation are: increased surface reflectivity, physical resistance of salt crust to water flow, and suppression of vapour pressure at the tailings surface due to osmotic suction (Fujiyasu and Fahey, 2000). Laboratory and field observations have shown the contribution of surface reflectivity to reduction in evaporation to be significant but not sufficiently large to explain the scale in the reduction of evaporation (Simms et al., 2007), indicating either or both other factors may be important. For the current paper, surface reflectivity was ignored by conducting drying experiments under ambient lighting as opposed to simulated radiant energy.

This paper examines the effect of osmotic suction of evaporation by tracking the mass transport of dissolved ions within desiccating thickened gold tailings. The long term goal of this research is to model the transport of ions to the surface and therefore to be able to predict the increase in osmotic suction and the associated reduction in evaporation. The relative contribution of osmotic suction and physical resistance of salt crust to water flow on evaporation is discussed. Conclusions from the current study and some practical tips for minimising the negative consequence of salinity on evaporative densification of thickened tailings stacks are also highlighted.

2 Laboratory methodology

2.1 Petroleum jelly wax-column technique for preparing and sampling desiccating thickened tailings columns

Khasawneh and Solileau (1969) proposed the petroleum jelly wax-column technique (PJWCT) as a convenient way of preparing soil columns for diffusion experiments, such that sections as thin as 5 mm can be obtained for various analyses. The technique has since been modified for studying ionic/fertiliser mobility in unsaturated soils (Khasawneh et al., 1974; Akinremi and Cho, 1991; Hao et al., 2000; Olatuyi et al., 2009). A mould with a cylindrical cavity for packing, drying and destructively sampling thickened tailings is made from a molten mixture of petroleum jelly (1.2 parts) and paraffin wax (3 parts). The schematic and dimensions of the wax column used in the current study is shown in Figure 1.

The cylindrical cavity of each wax column was packed with acid-generating thickened gold tailings at an initial gravimetric water content of 38%. The geotechnical properties and particle size distribution of the thickened tailings are shown in Table 1 and Figure 2, respectively. The initial pore-water solute composition of the thickened tailings is presented in Table 2. The bulk thickened tailings sample was thoroughly mixed mechanically prior to packing the wax columns to ensure homogenous pore-water composition. The packed columns were left to desiccate in the laboratory, with the total initial weight of each tailings column recorded at the beginning of each experiment. One tailings column was destructively sampled for various analyses at predetermined intervals by sectioning the tailings column into 1 cm thick slices by means of an adjustable hacksaw (Mastercraft Canada, Toronto ON) and a Jobmate plastic mitre box (Trileaf Distribution Canada, Toronto ON) used as a cutting guide. It was ensured that the tailings samples were not cross-contaminated and minimally disturbed during the sampling.

2.2 Experimental conditions and analyses

A total of 9 thickened tailings columns at 100% initial degree of saturation were prepared at the beginning of the drying experiment. An additional wax column was filled with deionised water and left exposed to ambient conditions for determination of potential evaporation rates (PE) throughout the experiment. All the packed columns and PE column were left to desiccate under room temperature and ambient lighting, with wind simulated by means of an oscillating fan placed at one end of drying platform. Initial calibrations with the fan showed a PE of between 8 and 12 mm/day, with no significant variation in PE due to location of wax column on the drying platform. Ambient temperature and relative humidity during the experiment was recorded by means of a USB-502 RH / Temperature Data Logger (Measurement Computing, Norton, MA). Following the procedure previously described, one tailings column was destructively sampled on days 3, 5, 7, 9, 11, 13, 14 and 15. The actual evaporation rates (AE) from packed columns as well as PE were determined by mass difference at the beginning of each sampling event.

Profile samples obtained from sectioning tailings columns were placed and homogenised manually inside Ziploc plastic bags prior to analyses. The Ziploc bags were sealed after expelling excess air in order to minimise potential oxidation of constituent sulphide minerals. Analyses conducted on thickened tailings samples include electrical conductivity (EC), gravimetric water content (GWC) and total suction determinations. For EC analysis, a 1:5 tailings slurry (tailings: deionised water) was extracted by means of an orbital shaker (175 rpm for 30 minutes) followed by centrifuging at 3,000 rpm (*1,000 X g*) for 2.5 minutes. The EC of clear supernatant was then determined using a previously-calibrated Traceable Conductivity Meter (VWR International, Friendswood, TX). The GWC of the samples were determined by difference in mass after placement in oven at 105°C for 24 hours. Also, the profile total suction for sampled column was determined using a WP4-T Dewpoint PotentiaMeter (Decagon Devices Inc., Pullman, WA). The profile matric suction of the sampled thickened tailings columns was inferred using the gravimetric water content data and the soil water characteristic curve of the thickened tailings (Figure 3) fitted by Fredlund and Xing (1994) equation. The osmotic suction was obtained by difference between corresponding total and matric suction values.

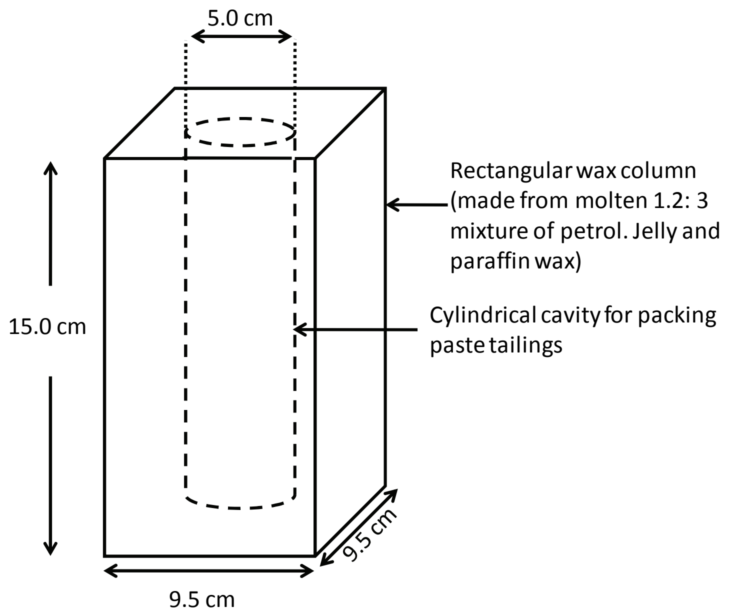

Figure 1 **Schematic diagram and dimensions of petroleum jelly wax column used for packing and drying thickened tailings**

Table 1 **Geotechnical properties of thickened gold tailings (after Simms et al., 2007) and artificial silt (after Fisseha et al., 2007)**

Property	**Thickened Tailings**	**Artificial Silt**
Specific gravity	2.9	2.48
D10, D50, D60 (microns)	2, 35, 55	1, 31, 41
Cu (D60/D10)	27.5	41
Liquid limit (%)	20	19
Plastic limit (%)	19	13
Saturated hydraulic conductivity (m/s)	2.0E-7	1.7E-6

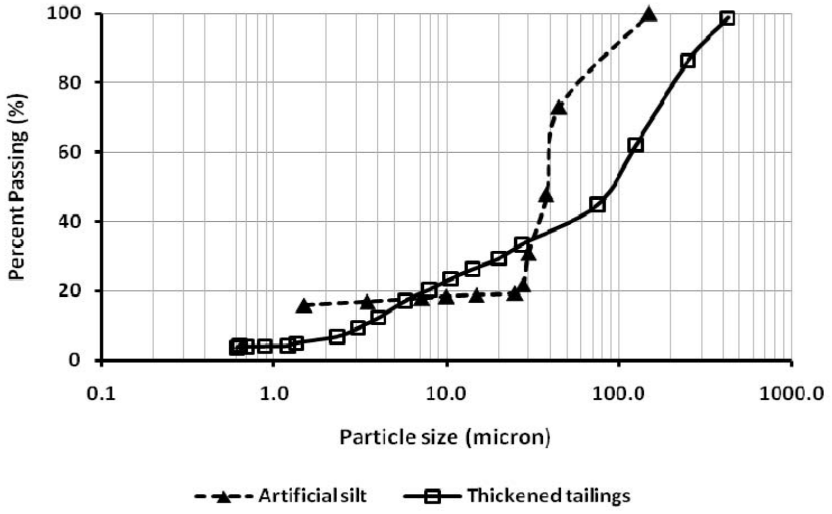

Figure 2 **Particle size distributions (PSD) of thickened gold tailings (determined by hydrometer and sieve analyses) and artificial silt (determined by hydrometer method)**

Table 2 Pore-water solute composition of thickened gold tailings (Bryan, 2008)

Ion	Concentration (mg/L)
SO_4^{2-}	2,140
Ca^{2+}	545
Mg^{2+}	125
K	283
Al	<0.1
Cu	0.07
Fe	<0.3
Pb	<0.01
Mn	2.8
Si	5
Zn	0.8
pH	6.93
Saturated thickened EC (mS/cm)	4.25

The experimental procedure previously described was followed in preparing wax columns using soil (artificial silts) with comparable geotechnical properties and pore-size distribution as the thickened gold tailings (Table 1 and Figure 2). This was done for the purpose of comparison of results from candidate thickened tailings to saline soil. All laboratory conditions and analyses for the saline soil were similar to that of the thickened tailings. The only difference was that the soil was prepared at 30% GWC to an homogenous pore-water salt concentration of 0.20 (mass of salt/mass of solution) using a reagent-grade NaCl (Lot # 8J9286; Purity > 99.0%; BioShop Canada Inc., Burlington, ON). The initial EC and Na^+/Cl^- concentration of 1:5 extract of the prepared silt slurry were 19 mS/cm and 52 parts per thousand, respectively. A control soil column similar to the saline soil column, but with no salt supplementation was also prepared, and subjected to same laboratory conditions throughout the drying experiment as the thickened tailings and saline soil columns.

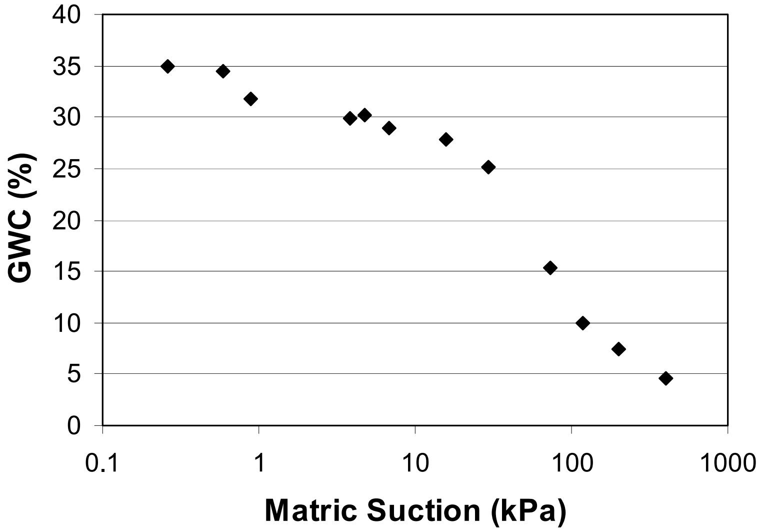

Figure 3 Soil water characteristic curve of thickened gold tailings (Simms et al., 2007)

2.3 Measuring and predicting relative evaporation from desiccating thickened tailings columns

The relative evaporation (RE) defines a ratio of actual evaporation (AE) from a tailings column to the potential evaporation (PE), and represents a normalised evaporation rate of a tailings layer (Fujiyasu and Fahey, 2000). The RE from each sampled tailings column was determined from the measured AE and PE values. RE is fundamentally controlled by the vapour pressure gradient between the tailings surface and the atmosphere. Vapour pressure at the surface changes as a function of total suction at the surface, and therefore RE can be predicted using the following equation (Wilson et al., 1997):

$$\frac{AE}{PE} = \left(\frac{e^{-\left(\frac{\psi W_v V_w}{RT}\right)} - h_a}{1 - h_a} \right) \tag{1}$$

Where:

ψ = total suction at surface (kPa).

W_v = the molecular weight of water (18.016 kg/mol).

V_w = the specific volume of water (1/998 m^3/kg).

R = universal gas constant (8.314 J/mol.K).

T = temperature of air above tailings column (K).

h_a = relative humidity of air above tailings column (%).

Total suction comprises both osmotic suction (resulting from dissolved solute in tailings pore-water) and matric suction (arising from the net capillary force of solid and air phases on the tailings water phase) (Agus and Schanz, 2005). Therefore, in drying thickened tailings, total suction increases both due to the increase of matric suction resulting from desaturation and the increase in osmotic suction arising from concentration of dissolved ions at the surface by evaporation-driven advection. Equation (1) was used to estimate RE and compared with the measured values to see if the suppression of vapour pressure alone could explain observed decreases in evaporation.

3 Results

3.1 Profile EC, gravimetric water content, total and matric suctions of thickened tailings

The profile total suction values for thickened tailings columns sampled on days 0, 3, 11 and 15 are shown in Figure 4. General trend observed was high total suction at the top 2 cm of the thickened tailings layer. The highest total suction values were consistently observed at the top 1 cm of the tailings layer (Figure 4), significantly increasing in value as desiccation of the thickened layer progressed. The total suction values decrease with depth within the thickened layer, generally approaching the as-deposited values at depths within the profile (Figure 4).

The profile electrical conductivity data is presented in Figure 5. By day 3 of drying the thickened tailings columns, the EC of the top 1 cm had slightly increased while the values at depths of 2 cm to 5 cm slightly decreased from the as-deposited values (Figure 5). On days 7 and 11, the EC values throughout the thickened tailings profile have increased, with the values at the top 1 cm having significantly increased to about four and five times the as-deposited values, respectively. Generally speaking, the profile EC tended to be uniformly distributed at depths beyond 2 cm within the thickened tailings layer (Figure 5).

Figure 6 shows the profile gravimetric fronts for the sampled thickened tailings columns throughout the drying experiment. There was a very rapid drying of the tailings columns for the first seven days of the experiment, during which as high as 74% reduction in the as-deposited GWC (38%) was observed

(Figure 6). Beyond day 7, only very slight reductions in GWC were noticed for the thickened tailings columns. Generally speaking, the same trend of reduction in GWC was observed at all depths of the sampled tailings column, indicative of a uniform drying regime within the thickened tailings layer. Similar trend in profile GWC is coincident with uniform profile EC at depths beyond 2 cm of the thickened tailings layer (Figure 5). Further evidence of uniform profile drying is shown with the matric suction evolution at various depths during desiccation being similar up until day 7 (Figure 7). After day 7, the general trend was the matric suction at the top 1–3 cm being slightly higher than the values for the rest of the profile.

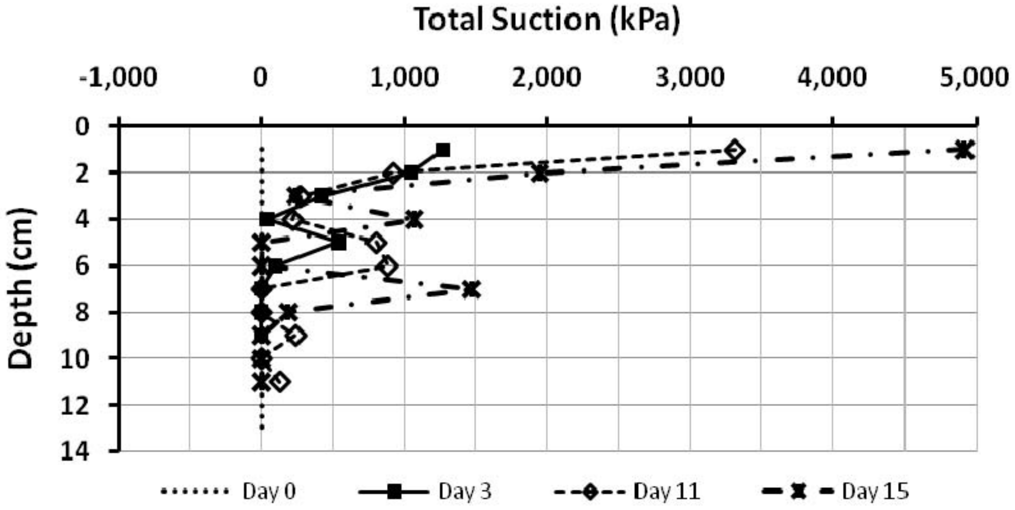

Figure 4 **Profile total suction for desiccating thickened tailings columns**

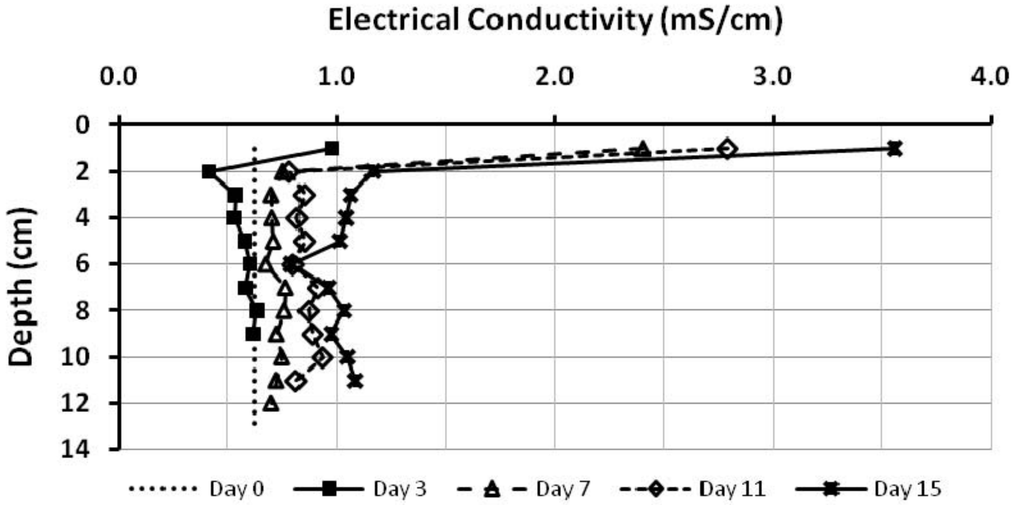

Figure 5 **Profile electrical conductivity for desiccating thickened tailings columns**

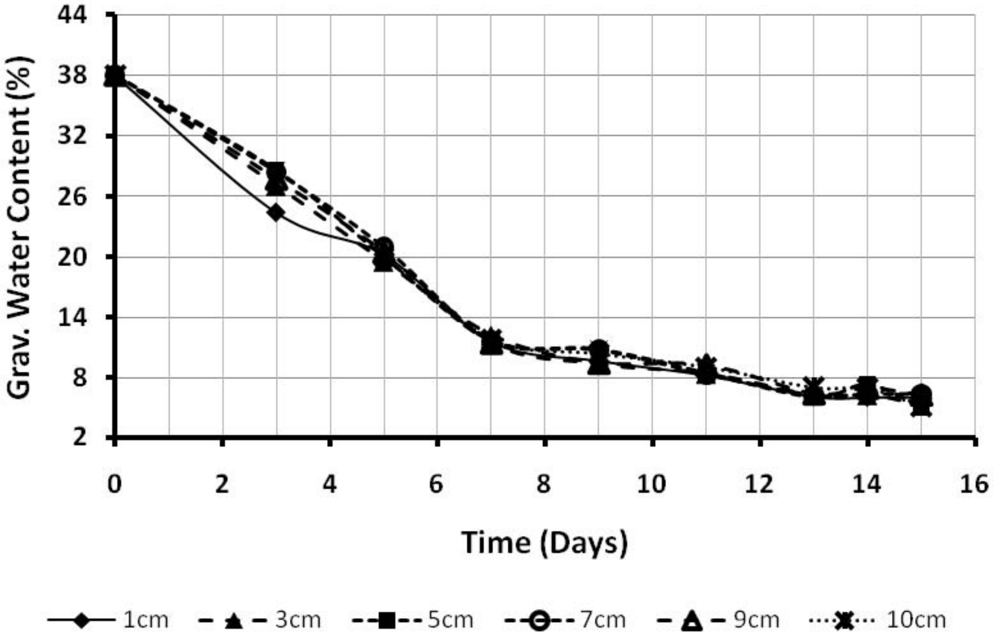

Figure 6 Profile gravimetric water contents of drying thickened tailings columns

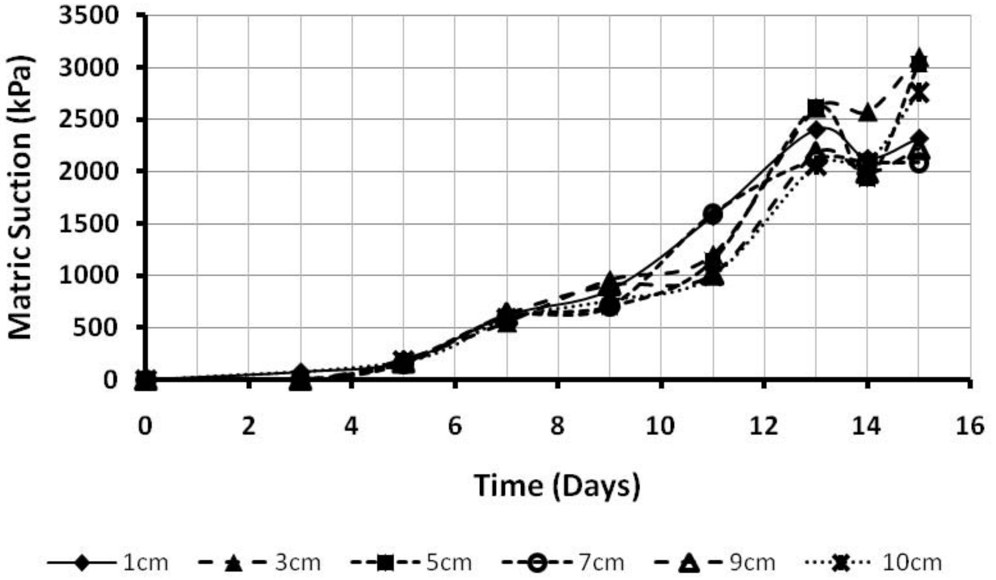

Figure 7 Profile evolution of matric suction for drying thickened tailings columns

The evolution of total, matric and osmotic suctions at the top 1 cm of thickened tailings column is presented in Figure 8. There was a rapid increase in both the total and osmotic suctions at the top 1 cm over the first nine days of drying (Figure 8). The increase in total suction continued throughout the experiment, but osmotic suction decreased steadily from days 9 to 13 before increasing again till the end of experiment. As expected, the EC data for the top 1 cm of layer follow the same trend as the osmotic suction (Figure 8). The matric suction also increased, but at a relatively lower rate. With the exception of days 13 and 14, osmotic suction was consistently higher than matric suction at the top 1 cm of thickened tailings layer. Therefore, osmotic suction was the major contributor to total suction compared to matric suction.

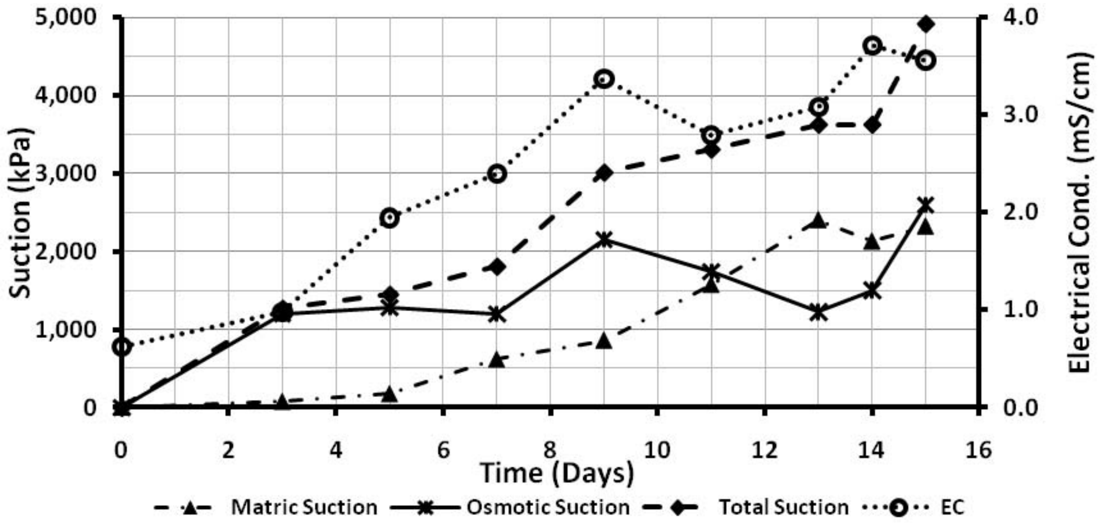

Figure 8 EC, total, osmotic and matric suction evolution at top 1 cm of desiccating thickened tailings

3.2 Measured and predicted evaporation rates from desiccating thickened tailings columns

As shown in Figure 9, the PE measured during the experiment ranged between 3.9 to 6.2 mm/day. The AE measured from the thickened tailings columns ranged from 3.2 to 5.7 mm/day, slightly increasing for the first 7 days of drying and consistently decreasing afterwards (Figure 9). By day 9, about two-thirds of total actual evaporation from thickened tailings columns has been recorded. This coincides with the total and osmotic suctions steadily increasing over the first nine days of drying the thickened tailings (Figure 8) as well as sharp drop in the profile GWC over the first 7 days of drying (Figure 6).

Figure 9 also shows the AE from drying thickened tailings columns predicted from the total and osmotic suctions at the top 1 cm of tailings layer, using Equation (1). For the most part, there was fairly good agreement between the AE measured and predicted for the tailings columns (Figure 9). More importantly, there was no difference in the AE predicted from total suction and osmotic suction at the top 1 cm of the thickened tailings. This coincides with the osmotic suction being the major contributor to total suction, relative to matric suction (Figure 8). Also, the AE measured and predicted for drying thickened tailings increasing for the first seven days of deposition coincides with the profile GWC for entire tailings layer rapidly decreasing over the same period (Figure 6).

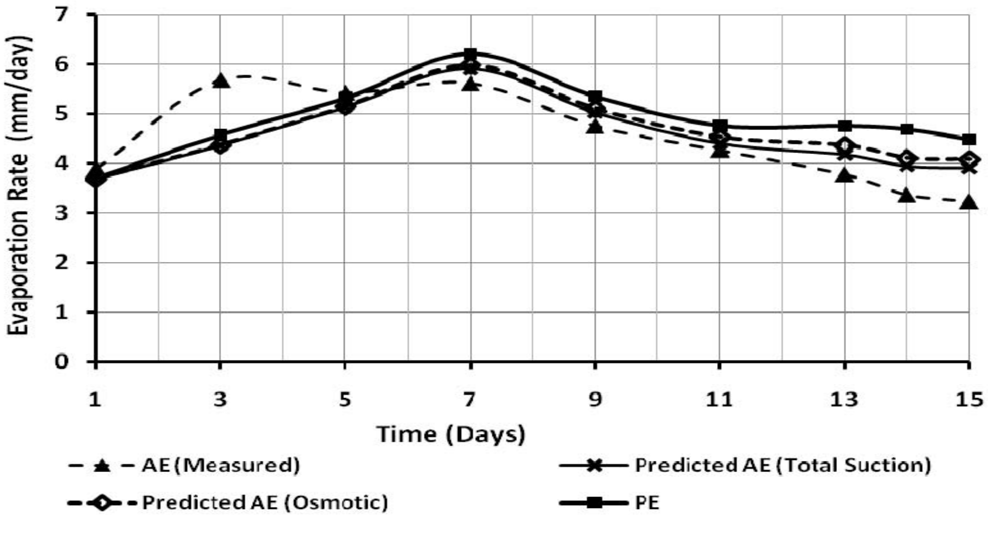

Figure 9 Potential evaporation rates during experiment and actual evaporation rates measured and predicted from total and osmotic suction at top 1 cm of desiccating thickened tailings columns

3.3 Comparison of results from thickened tailings to saline soil columns

Figure 10 shows results from column drying experiments with saline soil (C = 0.20) and non saline soil (C = 0) under laboratory conditions similar to the thickened tailings columns. The actual evaporation rates from the saline soil was observed to be reduced to just a fraction of the values for the non-saline equivalent. This difference in evaporation rates resulted in a 90% reduction in gravimetric water content at top 1 cm for non-saline soil compared to just 54% reduction for the saline soil (data not presented here) after 14 days of drying.

The AE predicted from the total suction at the surface of the saline soil columns using Equation (1) is in general agreement with the AE measured from the same soil columns (Figure 10). The AE measured from the saline soil columns (Figure 10) is consistently only a fraction of the AE for the thickened tailings column (Figure 9). This is due to the extremely high total suctions at the surface of the saline soil (Figure 11) compared to the lower values for the drying thickened tailings (Figure 4). The saline soil has significantly higher as-deposited pore-water conductivity (~19 mS/cm) compared to the thickened tailings. Similar to the thickened tailings, the accumulation of salts occurred at the top 2 cm of the saline soil, as shown by the highest total suctions occurring at the surface (Figure 11). The total suction values for the rest of profile approached the as-deposited values at 4, 6, 7 and 10 cm depths on days 2, 4, 7 and 11, respectively.

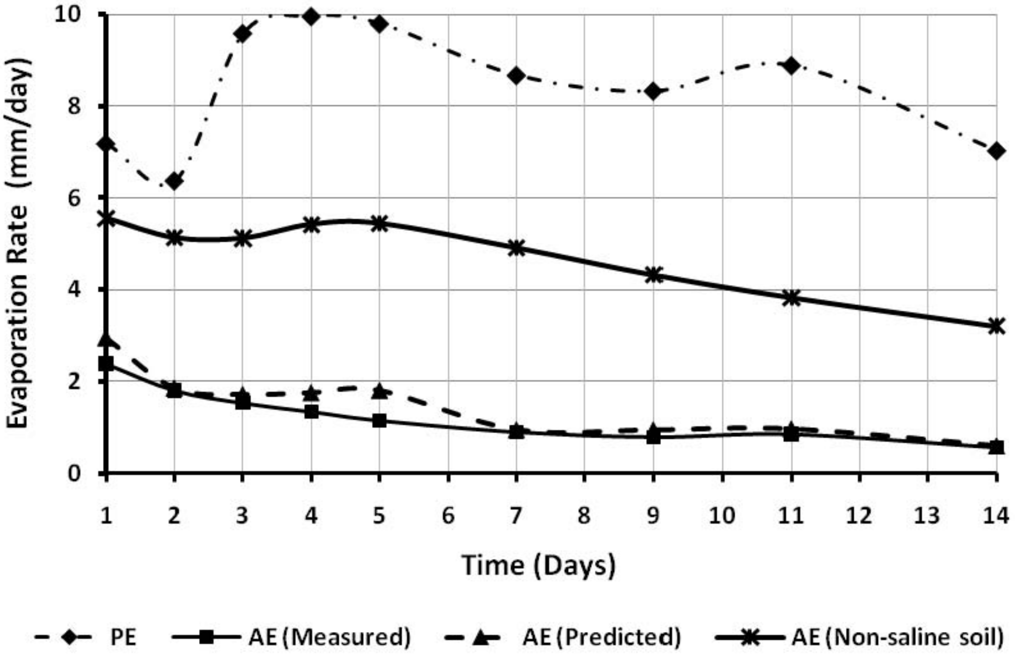

Figure 10 Potential evaporation during experiment, actual evaporation rates measured for desiccating saline and non-saline soils and AE predicted from total suction at top 1 cm of drying saline soil

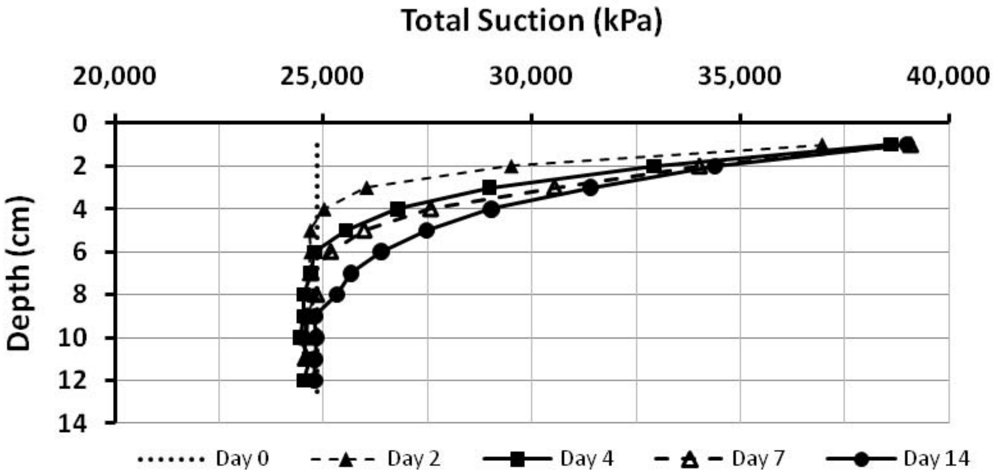

Figure 11 Profile total suctions for drying saline soil columns

4 Discussion

4.1 Effect of pore-water salinity on evaporative fluxes from thickened tailings deposits

Both the results from the thickened tailings and the saline soil show that the influence of salts on evaporation can be quantified by measured total suctions. This suggests that the slowdown of evaporation is at least initially independent of any change in the physical properties of the tailings, which in turn will allow engineers to make predictions of evaporation suppression based on mass-transport modelling alone.

Further tests on the thickened tailings using thicker layers and longer drying periods and for multilayer deposition are ongoing. Contaminant transport modelling of the type undertaken by Fisseha et al. (2009) is underway to see if the flux of ions to the surface can be predicted, and therefore, that the point of suppression of evaporation by salts can be predicted from knowledge of the initial pore-water chemistry. The authors anticipate that any contribution to dissolved mass through oxidation of sulphide minerals during deposition will not be significant, but this is also being evaluated.

4.2 Practical lessons for optimising evaporation rates from saline high-density tailings stacks

From practical standpoint, pore-water salinity can lead to slow rate of shear strength gain in thickened stacks and reduce the success rate of re-vegetating decommissioned thickened disposal facilities. The reduction in shear strength gain may be significant especially for hypersaline thickened tailings deposits or in applications where salt additives (such as lime or gypsum) have been added for dewatering purposes prior to surface deposition. To counter this, capillary break barriers may be constructed on top of old thickened tailings layer before deposition of fresh layer in order to stop further salt movement into the fresh layer (Newson and Fahey, 1997; Williams and Stolberg, 2006). Thinner layers and shorter deposition cycles would also minimise any salt accumulation, though as shown in Fisseha et al. (2009) it is possible for ions from multiple layers to eventually concentrate at the surface of the last placed layer. The authors suppose that salts can be therefore controlled through a combination of deposition planning with the occasional interlayer placement of a coarse-textured soil as a capillary break. The authors hope to be able to provide a simulation of alternative deposition schemes by the time of the conference to quantitatively demonstrate this point.

5 Conclusion

In the current study, the suppression of evaporation by salts can be quantified in terms of the osmotic effect alone. This finding is important as suppression of evaporation can be predicted by ion transport modelling of the kind proposed by Fisseha et al. (2009), without consideration of the effect of physical resistance by salt crusts on unsaturated flow in thickened tailings stacks. This will allow engineers to optimise deposition schemes to minimise or control the suppression of evaporation by salts.

Acknowledgement

This research is funded in part by Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery and CRD grants and an Innovation Alliance grant to the second author, and a NSERC scholarship to the first author. Barrick Gold was kind enough to supply the tailings.

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